Monitoring the Transportation Infrastructure with Satellite-Based Interferometric Synthetic Aperture Radar (InSAR)

A. Vaccari, M. Stuecheli, S. T. Acton
Virginia Image and Video Analysis (VIVA)
University of Virginia

B. S. Bruckno
Virginia Department of Transportation

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Disclaimer

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Overview of Presentation

- Problem Statement
- Relevance to transportation
- Technology and Data Collection
- Analysis method
- Results and Validation
- Conclusion and future work
Project: Problem Statement

Can InSAR technology be used to detect and monitor ground features of interest to the transportation community?

In particular, can leading edge satellite-based interferometric techniques provide a proactive rather than reactive approach to potentially hazardous phenomena such as **sinkholes**, landslides and bridge displacement?

(InSAR: interferometric synthetic aperture radar)
Relevance to Transportation

• Increased Safety:
  – Increase safety of the traveling public and reduce the liability exposure to a DOT

• Reduced inconvenience for public:
  – Reduce delays associated with highway closure

• Reduced Costs (VDOT):
  – Emergency costs:
    • Typically 2 to 5 times higher than standard maintenance
  – High individual costs:
    • Minimum cost per sinkhole: $25k
  – High aggregate costs:
    • About $1.2M/year for sinkholes and landslide in central VA
InSAR Technology: Satellite

- Active System
- Not affected by weather

COSMO-SkyMed1

- Epoch (UTC): 06 May 2013 12:40:34
- Eccentricity: 0.0001324
- Inclination: 97.8736°
- Perigee height: 621 km
- Apogee height: 623 km
- Right ascension of ascending node: 312.4119°
- Argument of perigee: 82.6105°
- Revolutions per day: 14.82172081
- Mean anomaly at epoch: 277.5294°
- Orbit number at epoch: 31986
InSAR Technology: Satellite

SAR Satellites: Past, Present and Future


ERS1 - ERS2
ENVISAT
RADARSAT-1
RADARSAT-2
ALOS-PALSAR
ALOS
TerraSAR-X
Tandem-X
Cosmo Sky-Med Constellation
Cosmo Sky-Med 2
SADCOM 1A
Sentinel-1
RCM Constellation

Slide 7
8/6/2013
InSAR Technology: Theory

\[ \Delta R \]

R1

R2
Differential InSAR

InSAR Technology: Products

PSInSAR™ uses at least 15 images

- only stable radar targets (PS) on the ground are used for measurements
- atmospheric effects removed
  ➔ measurements have millimeter accuracy
- now have a history of motion
InSAR Technology: Products

SqueeSAR™

PS

DS

No data

Received signal

Signal

Range

DS

PS
InSAR Technology: Products

PSInSAR™  SqueeSAR™

[Images of PSInSAR™ and SqueeSAR™ product examples]
InSAR Technology: Data sets

Sinkholes
InSAR Technology

Advantages:
- Active system
- Large coverage in short time
- Short repeat times
- Very high displacement resolution
- Time series of displacements

Shortcomings:
- Moderate starting ground resolution (3x3m)
- Expensive (COSMO-SkyMed: 3600€/scene)
Modeling phenomena

- What is the ground deformation?
- How does it evolve in time?
- Link behavior to underlying geophysics
Sinkholes data set

- 93,513 PS+DS points
- 22 Single look complex SAR
- ERS Satellites
- June 1992 to February 1998
- 55km² near Wink, SW Texas
Profile extraction
Spatiotemporal model

Evolving Gaussian?

\[ g_t(x) = \alpha_t \exp\left(-x^2/2\sigma_t^2\right) \]
Spatiotemporal model

Evolving Gaussian! \[ g(x, t) = \alpha t \exp\left[ -\frac{(x - x_0)^2}{2\sigma^2} \right] \]
Feature Tracking: Approach

- Spatio-Temporal Model
- Parameter Space
- InSAR Stack
- Residual Map
Feature Tracking: Theory

\[ g_p(x, t) = \alpha \exp \left[ -\frac{(x - x_0)^2}{2\sigma^2} \right] \]

Relative residual:

1. Rewrite model in implicit form
   \[ T(x, p) = 0 \]

2. Discretize and limit the parameter space \( p = [x_0, \alpha, \sigma] \)
   \[ p_{min} \leq p \leq p_{max} \quad \text{with step: } \Delta p \]

3. Define a residual matrix \( r(p) \) with one element corresponding to each point \( p \) in the parameter space

4. For each point \( p \) in the parameter space generate the corresponding template \( g_p(x_i, t) \) and define and influence region \( R(p) \)

5. For each data point \( x_i \) within \( R(p) \) evaluate the relative residual

\[ \mu(x_i, t) = \min \left( \frac{|d(x_i, t) - g_p(x_i, t)|}{\max(|d(x_i, t)|, |g_p(x_i, t)|)}, 1 \right) \]

6. Average results within \( R(p) \rightarrow r(p) \)

Validation: Sinkholes data set

- 93,513 PS+DS points
- 22 Single look complex SAR
- June 1992 to February 1998
- ERS Satellites
- 55km² near Wink, SW Texas
Central Virginia data set

- 166,348 PS + 129,773 DS
- 32 Single look complex SAR
- August 2011 to October 2012
- COSMO-SkyMed Satellites
- 40x40km² Augusta County, VA
- USDOT RITARS-11-H-UVA
Central Virginia data set
Central Virginia data set

Residual: $r(p) = r(x_0, y_0, \alpha, \sigma)$

Risk: $\rho(p) = [1 - r(p)]\exp\left(\frac{1}{\alpha_p}\right)$

- $\rho(p) \geq 0.475$
- $0.40 \leq \rho(p) < 0.475$
- $0.35 \leq \rho(p) < 0.40$
## Central Virginia data set

Credit: Brian Bruckno, Ed Hoppe, VDOT, VCTIR

<table>
<thead>
<tr>
<th>Categories</th>
<th>Infrastructure</th>
<th>Geomorphology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolute (A)</td>
<td>Cracks, settlement</td>
<td>Recent non-vegetated scarps</td>
</tr>
<tr>
<td>Strong (S)</td>
<td>Distortions or cracks</td>
<td>Overgrown scarps</td>
</tr>
<tr>
<td>Weak (W)</td>
<td>Repairs or cracks</td>
<td>Geomorphology indicates activity</td>
</tr>
<tr>
<td>Possible (P)</td>
<td>Near existing active region</td>
<td>In correct terrain, presence of pinnacles</td>
</tr>
<tr>
<td>None (N)</td>
<td>No or negative confirmation</td>
<td>No or negative confirmation</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Risk</th>
<th>Evaluated</th>
<th>A</th>
<th>S</th>
<th>W</th>
<th>P</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Severe</td>
<td>7</td>
<td>4 (57%)</td>
<td>2 (29%)</td>
<td>-</td>
<td>-</td>
<td>1 (14%)</td>
</tr>
<tr>
<td>Moderate</td>
<td>15</td>
<td>8 (54%)</td>
<td>2 (13%)</td>
<td>2 (13%)</td>
<td>1 (7%)</td>
<td>2 (13%)</td>
</tr>
<tr>
<td>Slight</td>
<td>10</td>
<td>5 (50%)</td>
<td>4 (40%)</td>
<td>-</td>
<td>1 (10%)</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>32</td>
<td>17 (53%)</td>
<td>8 (25%)</td>
<td>2 (6%)</td>
<td>2 (6%)</td>
<td>3 (10%)</td>
</tr>
</tbody>
</table>

25 (78%)
Extension to different models

- Extensible method
- Feature tracking
  - Spatio-temporal model
  - Model parameters
- Risk assessment
  - Based on residual map
  - Allow inclusion of external knowledge
Field Validation: Vesuvius Sinkhole
Credit: Brian Bruckno, Ed Hoppe, VDOT, VCTIR
Field Validation: Vesuvius Sinkhole
Field Validation: Rock Slopes

Analyze:

- Low-angle Wedge Failures
- Broad Failure Mode
- Field Conditions

ESRI ArcMap 10.0
Field Validation: Rock Slopes

Confirmed:

VEL: -1.75mm/yr
Field Validation: Rock Buttress Stability

Field Validation of InSAR Data:

Temporal series of scatterers subset
Field Validation: Rock Buttress Stability

Field Validation of InSAR Data:
Field Validation: Bridge on Route 635 over I-81

Mapping of the bridge with points of interest labeled as TS1 and TS2. The map shows a gradient of surface displacement rate with values ranging from -10 to 10 mm/year. The map projection is StatePlane Virginia North FIPS 4501 (Feet) / NAD1983. Imagery courtesy of the Commonwealth of Virginia, © TRE Canada 2012.
Field Validation: Bridge on Route 635 over I-81
Field Validation: Bridge on Route 635 over I-81
Mobile Devices Deployment

- Proof of concept
- LAMP (Linux, Apache, MySQL, PHP) server
- Real time database query and update
- Google Maps API
Project: Future Work

• Extend tested sinkhole algorithm (e.g. bridge and landslide spatio-temporal models)

• Develop pavement condition index based on temporary scatterers

• Develop Risk mapping algorithm based on existing and learned data
Thank you!